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REVIEW OF ADVANCED RADIATOR TECHNOLOGIES FOR SPACECRAFT POWER SYSTEMS AND SPACE THERMAL CONTROL

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Summary

The thermal management of manned spacecraft traditionally has relied primarily on pumped, single-phase liquid systems to collect, transport, and reject heat via single-phase radiators. Although these systems have performed with excellent reliability, evolving space platforms and space-based power systems will require lighter, more flexible thermal management systems because of the long mission duration, large quantities of power system cycle reject heat, and variety of payloads involved. The radiators are critical elements in these thermal management systems. This report presents a two-part overview of progress achieved in space radiator technologies during the eighties and early nineties. Part I contains a review and comparison of the innovative heat-rejection system concepts proposed during the past decade, some of which have undergone preliminary development to the breadboard demonstration stage. Included are space-constructable radiators with heat pipes, variable-surface-area radiators, rotating solid radiators, moving-belt radiators, rotating film radiators, liquid droplet radiators, Curie point radiators, and rotating bubble-membrane radiators.

Part II contains a summary of a multielement project effort, including focused hardware development under the Civil Space Technology Initiative (CSTI) High Capacity Power program. A key project under this program carried out by the NASA Lewis Research Center and its contractors was the development of lightweight space radiators applicable to the Space Exploration Initiative (SEI) power systems technologies. Principal project elements include both contracted and in-house efforts conducted in a synergistic environment designed to facilitate accomplishment of project objectives. The contracts with Space Power Inc. (SPI) and Rockwell International are aimed at development of advanced radiator concepts, whereas the in-house work has been guiding and supporting the overall program with system integration studies, heat pipe testing, analytical code development, radiating surface emissivity enhancement, and composite materials research to develop and analyze lightweight, high-conductivity fins. These tasks are key prerequisites in the effort to reduce specific mass of space radiators.

Introduction

The traditional means for rejecting heat from manned spacecraft are heat-rejection systems composed of single-phase fluid loops (Peterson 1987). These single-phase fluid loops use a mechanically pumped coolant to transfer heat from the habitation portion of the spacecraft to the radiators where it is rejected to the space environment. Although these systems have performed with excellent reliability in the past, evolving space platforms and space-based power systems will require more flexible thermal management systems because of the multiyear mission durations, large quantities of heat to be rejected, long physical distances, and large variety of payloads and missions that must be accommodated (Mertesdorf et al. 1987).

In general, space thermal management systems, whether serving life support or future space power systems, consist of three separate subsystems:

(1) A heat acquisition subsystem that collects heat from the various payload or power system heat-rejection interfaces
(2) A heat transport subsystem that transports heat from the acquisition sites to the radiating surfaces
(3) A heat-rejection subsystem composed of radiating surfaces that form the space radiator

An example of a typical space thermal management system proposed for large space platforms, namely a two-phase heat-rejection system consisting of the subsystems listed above, was presented by Edelstein (1987). These three subsystems comprise a thermal utility that would employ the high latent heat of a working fluid to transport heat from its acquisition sources to the radiators, where it would be rejected by radiation to the particular space environment.

The last of the three subsystems, the radiators, are critical components of virtually all proposed space-borne installations. In most current designs, the radiator is composed of an array of tubes or tube-fin structures through which liquid coolant is circulated. The tube wall must be sufficiently thick to minimize micrometeoroid penetration. As a result, the radiator mass could comprise as much as half of the total system mass (Juhasz and Jones 1987).

The technical challenges associated with the development of heat-rejection systems capable of meeting future requirements have been described previously (Ellis 1989). Presented here is a review and comparison of the heat-rejection systems that have been proposed for development for space platforms and space-based power systems.

The first part discusses innovative concepts that have undergone only limited development but are documented for potential future consideration. These include space-constructable radiators, variable-surface-area radiators, rotating solid radiators, moving radiators, and rotating bubble-membrane radiators.

The second part contains a summary of a multielement project effort including focused hardware development under the CSTI High Capacity Power program carried out by the NASA Lewis Research Center and its contractors for the purpose of lightweight space radiator development in support of Space Exploration Initiative (SEI) power systems technology. Principal project elements include both contracted and in-house efforts conducted in a synergistic environment designed to facilitate accomplishment of project objectives. The contracts with Space Power Inc. (SPI) and Rockwell International are aimed at development of advanced radiator concepts, whereas the in-house work has been guiding and supporting the overall program with system integration studies, heat pipe testing, analytical code development, radiating surface emissivity enhancement, and composite materials research aimed at development and analysis of lightweight, high-conductivity, high-emissivity fins. These tasks are considered to be key prerequisites in the effort to reduce specific mass of space radiators.

Part I.—Innovative Radiator Technologies

Space-Constructable Heat Pipe Radiator

The heat-rejection system presently used on the space shuttle orbiters consists of over 250 small, parallel tubes embedded within a honeycomb structure. Warm, single-phase Freon from the heat collection and transport circuit is circulated through these tubes (fig. 1). Heat is transferred from the coolant by convection to the tube walls, conduction through the honeycomb structure, and finally, radiation to space. Application of this technology to the station heat-rejection subsystem would require over 750 interconnected tubes. Moreover, if only a single redundant loop were used, a puncture in any single tube could disable the entire system, making this type of system infeasible for long-term missions.

A space-constructable radiator (SCR), composed of a series of individually sealed heat pipe elements similar to that shown in figure 2, has been proposed (Ellis 1989), and several advantages of this type of system over pumped single-phase fluid loops have been identified. These advantages include a significant reduction in weight due to the reduction in fluid inventory, increased heat-rejection capacity due to the uniform temperature of the radiating surface, and increased reliability, because penetration by a single micrometeoroid or piece of space debris would result in the failure of only a single heat pipe element and therefore cause only a slight degradation in performance.

High-capacity, SCR elements have been investigated in several shuttle flight experiments, including the STS–3 flight

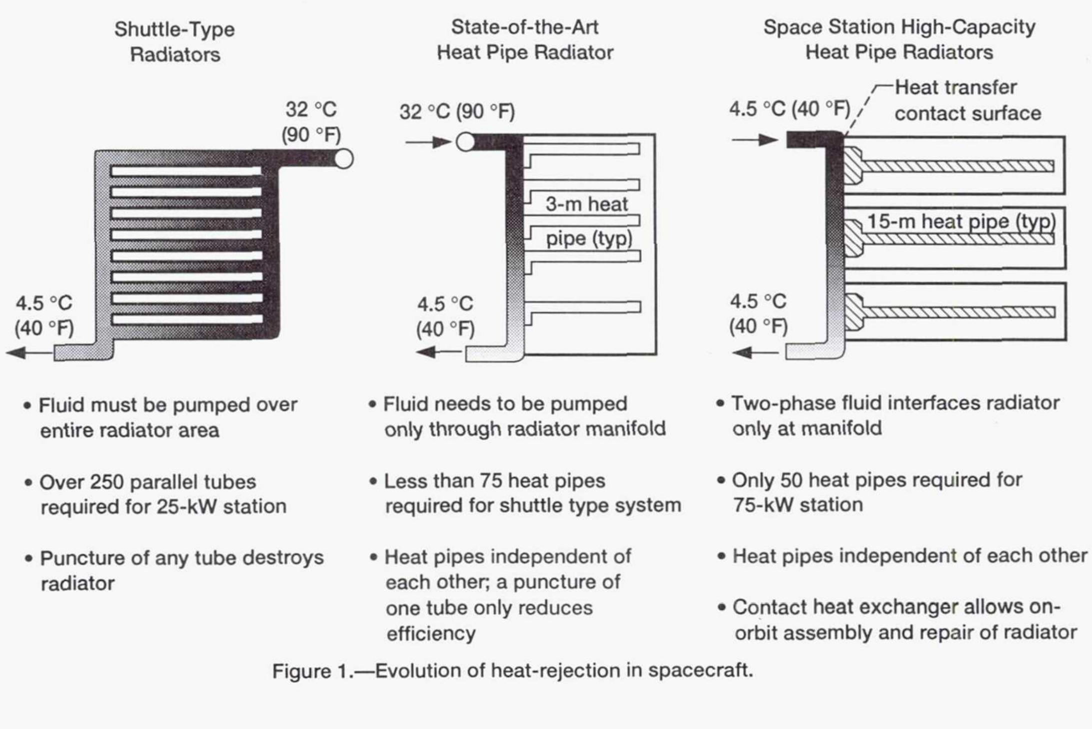

Figure 1.—Evolution of heat-rejection in spacecraft.

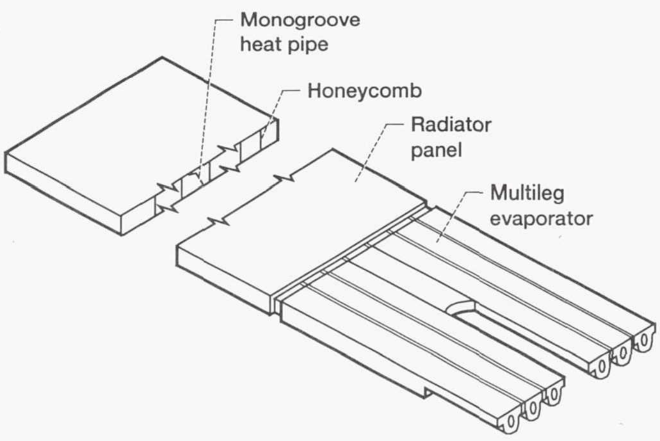

Figure 2.—Space-constructable radiator panel configuration.

of the Thermal Canister (Harwell 1983), the STS–8 Heat Pipe Radiator Experiment (Alario 1984), and the recent Space Station Heat Pipe Advanced Radiator Element (SHARE) flight test (Rankin, Ungar, and Glenn 1989; Kossan, Brown, and Ungar 1990). Results of these three flight tests, along with those of numerous ground tests, have demonstrated that heat pipe radiators present a feasible alternative to pumped single-phase systems.

In addition to the space station, such space-constructable heat pipe radiator systems could be utilized in solar dynamic (SD) power systems (Brandhorst, Juhasz, and Jones 1986; Gustafson and Carlson 1987). In this application, the radiators must reject the nonconvertible thermal energy portion of the total heat energy supplied to the power system. They thus represent a critical component of the overall development of space-based power systems. Figure 3 shows a typical SD power module design that incorporates a space-constructable heat pipe radiator system. As illustrated, the radiator could be segmented into several panels for redundancy, with a few excess panels incorporated to serve as backup spares for panels with degraded performance.

Although these space-constructable heat pipe radiators have performed adequately under realistic thermal/vacuum test conditions and during several shuttle flight tests, the application of this technology to an SD power system for the space station, for example, would require about 50 heat pipes, each 10 to 15 m long, to reject the 75 kW required by the 1989 space station design (Ellis 1989).

Variable-Surface-Area Radiator

The concept of a flexible, variable-surface-area radiator that can absorb high peak heat loads for brief time intervals was first introduced in 1978 (Leach and Cox 1977). These types of radiators can be classified into two major categories: (1) those in which no phase change occurs and (2) those in which the fluid changes phase. Oren (1982) gives the results of an investigation involving two types of flexible roll-out fin radiators in which no working fluid phase change was required. The first radiator had a rolled-up fin with a plastic or elastomeric tube attached to both sides. When gas pressurization was allowed to inflate the two tubes, the fin unrolled, and provided a substantial increase in the surface area. The second radiator used aluminum radiator tubes that were wound in the form of a helical spring configuration to form a cylinder covered by the fin material. This variable-surface-area radiator, which used the inherent spring force (similar to a jack-in-the-box) for deployment, was intended to meet heat-rejection needs of up to 12 kW (Leach and Cox 1977; Oren 1982). Because no phase change was required, an ethylene glycol/water solution was proposed as the working fluid.

Several types of variable-surface-area radiators that utilize a liquid vapor phase change and the associated increase in volume have been proposed. Figure 4 illustrates the proposed operation of these radiators. As shown, in their simplest form, these types of radiators are composed of two thin-walled sheets sealed along the edges and formed into a concentric roll. This roll extends, or rolls out, because of the increased vapor pressure generated by heating the wick structure in the evaporator. This wicking structure can, in some cases, line the inside of the entire fin to assist in liquid return. Once the vapor condenses, the fin curls back or retracts to the stowed position.

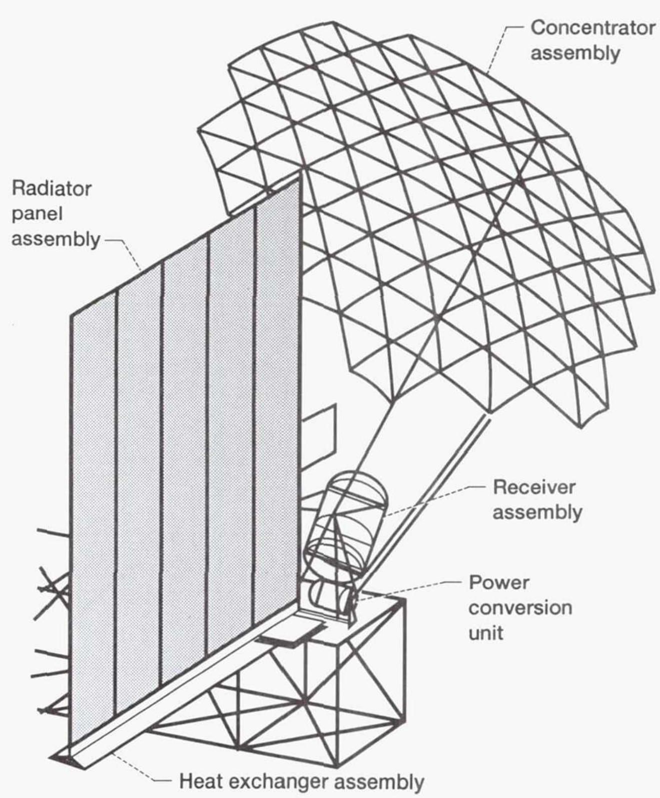

Figure 3.—Solar dynamic power module.

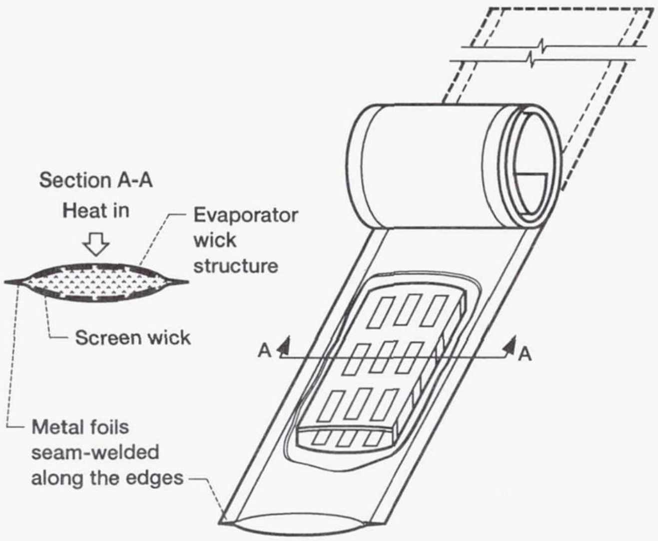

Figure 4.—Roll-out fin tubular segment.

Figure 5 illustrates the principle of operation for this type of radiator. Initially, the working fluid within the fin exists as a subcooled or saturated liquid (fig. 5(a)). Because of the flexibility of the fin, heat addition and rejection occur at constant pressure. Heat added to the evaporator vaporizes the working fluid, which expands, thereby causing the fin to extend (fig. 5(b)). This permits the entire external surface of the fin to radiate heat to space (fig. 5(c)). As the vapor condenses, the longitudinal stiffness causes the fin to curl into its original spiral shape, thereby squeezing the liquid droplets toward the evaporator (fig. 5(d)) where they can be stored in the capillary wick structure. In this system, maximum heat rejection occurs when the radiator is fully expanded. In a steady-state mode, the fin spring constant could be designed so that the length of the fin would automatically adjust to balance the heat input and rejection. Roll-out fins could be made from either a thin metallic foil or plastic film with an internal spring. In the case of metallic foil, the metal itself could be heat treated to act as a spring and provide the retraction force.

Several different variations of this device have been investigated, including radiators that employ the previously described principle (Ponnappan, Beam, and Mahefkey 1984), larger multicomponent expandable radiators (Chow, Mahefkey, and Yokajty 1985), and inflatable-expandable pulse power radiators. Ponnappan, Beam, and Mahefkey (1984) discussed the conceptual design of a 1 m long roll-out fin that could accommodate modest peak-to-average (10:1) heat loads by varying the projected surface area. This concept has been expanded to include radiator panels which utilize several of these roll-out fins in parallel to form panels (fig. 6). In this application, each of the four segments could function independently for a given pulsed or steady heat input condition, or the four panels could be arranged around a common vapor header and act jointly to reject heat.

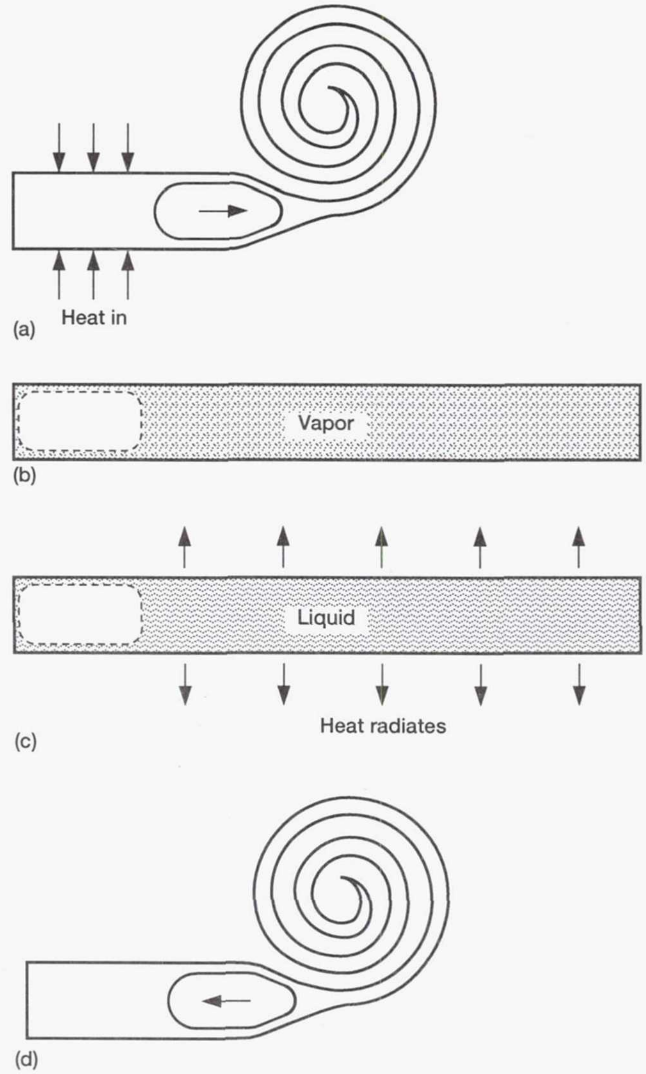

Figure 5.—Operation of a roll-out fin radiator. (a) Working fluid is a subcooled or saturated liquid. (b) Working fluid evaporates and expands, causing fin to extend. (c) Heat radiates to space. (d) Vapor condenses, and fin curls into original shape.

Figure 7 illustrates a concept similar to the roll-out fin; however in this situation, an inflatable bag system replaces the roll-out fin (Chittenden et al. 1988). The inflatable bags proposed for this concept would be made of a thin, strong, lightweight, internally lined or coated fabric with water as the working fluid. As illustrated, during the high heat absorption phase caused by a power pulse, the radiator bags would extend out of the spacecraft as they expanded with vaporization of the working fluid. Then, as the spacecraft continued orbiting, the vapor would condense as heat radiated to space. The radiator bags would retract during condensation, thus maintaining a constant internal saturation pressure, and they would fold into the spacecraft, ready to extend again during the next power pulse. As for the roll-out fin, this concept is characterized by a high condensation heat transfer rate inside the radiator, low

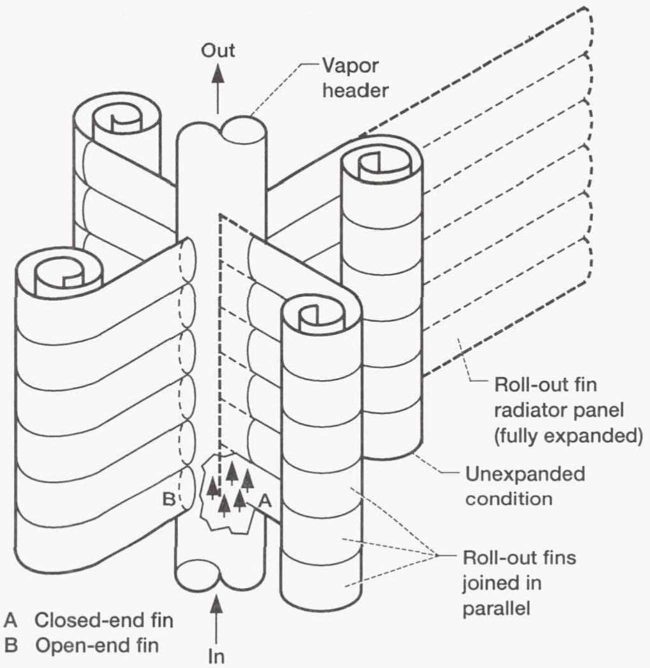

Figure 6.—Roll-out fin expandable radiator panel concept.

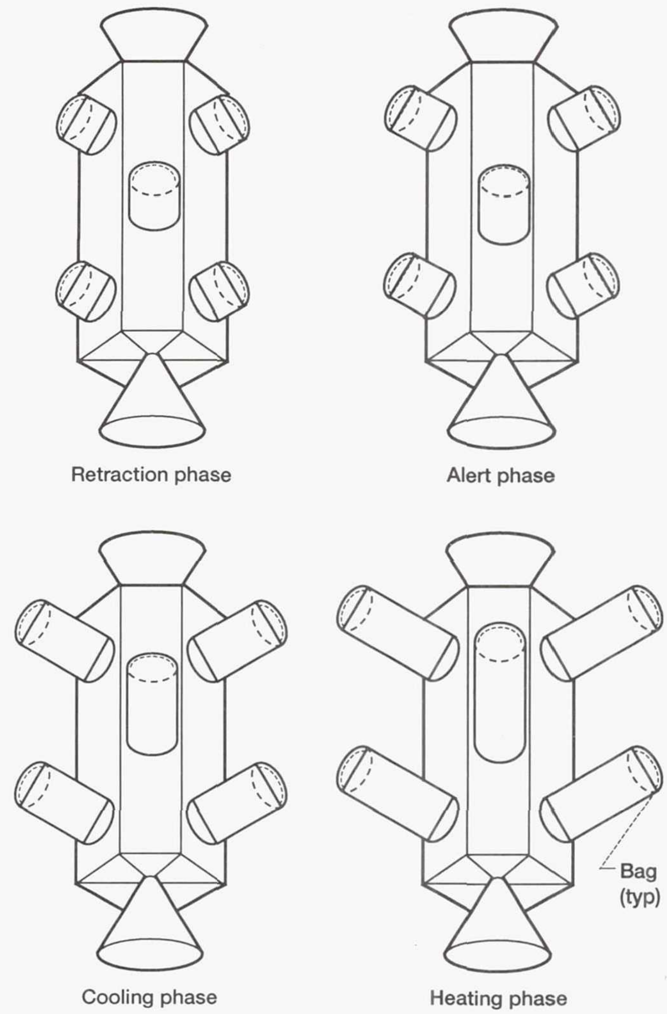

Figure 7.—Operational phase of high-power, inflatable bag radiator system.

operating fluid mass due to the large latent heat of vaporization, and high radiator effectiveness due to near isothermal operation. This type of radiator is capable of absorbing and storing substantial quantities of heat during the peak power phase of the duty cycle, and it can reject the stored heat during the longer time intervals of the cooling and retraction phase.

Studies of space Strategic Defense Initiative (SDI) missions showed requirements for peak electric power in the megawatt range. On the basis of these missions and their orbital cycles, radiator systems were required to be capable of rejecting heat absorbed in the form of short duration pulses with peak-to-average ratios of 10 000 or more (Mahefkey 1982). Present conventional radiators are sized to reject peak heat loads, and they are turned down by lowering heat transport fluid flow to reject off-peak loads. As a result, these conventional radiators are capable of near-constant-load thermal control over a range of nominally 10:1 peak-to-average heat loads. However, for high heat load, weight-constrained applications with very high peak-to-average ratios, conventional radiator designs would have limited applicability (Chow and Mahefkey 1986).

Elliott (1984) and Koenig (1985) suggested using expandable balloon radiators to provide ultra-lightweight surfaces. However, the utilization of expandable surfaces for cooling imposes a fundamental limit on operation time. In addition, a severe mass penalty is associated with periodic heat release. Since late l983, a collectable-expandable radiator, also known as the expandable pulse power radiator, has been investigated at the Air Force Aero Propulsion Laboratory (Chow and Mahefkey 1986). Basically, in this concept, a phase-change material cools high power-density devices through flash evaporation. The vapor is collected on an expandable, variable surface area (a thin metallic or plastic inner liner) on which it is allowed to condense during the time interval between pulses. The condensate is then pumped back (or returned by other means) to the coolant reservoir to be recycled.

Several possible expandable containers have been proposed. For high peak-heat-load pulsed radiators, low surface-to-volume inflatable bags or bellows radiators appear promising because of their large energy storage capacity (Chow, Mahefkey, and Yokajty 1985). The radiator would be constructed from a thin, low-density, flexible material that could be collapsed and stored in a compact form, ready for expansion during high peak heat loads. Because of the large volume-to-mass ratio, large amounts of vapor could be contained during the pulse period and rejected through condensation and radiation during the longer interpulse period. This design results in a lightweight radiator that is very compact in the stowed position and easily protected from micrometeoroid damage, except when in use.

Because of the high heat absorption and low heat-rejection rates of pulsed systems of this type, the duration of the pulse heating period must be shorter than the interval between the pulsed, high heat load cycles. This calls for stringent restrictions on the time response characteristics. For cases requiring higher energy pulses, an expandable bellows concept has also been proposed (Chow, Mahefkey, and Yokajty 1985). The bellows concept differs from the roll-out fin and inflatable bag concepts in that a significant amount of heat energy is stored in the expanding structure.

Rotating Solid Radiators

Sensible heat capacity heat-rejection systems were first proposed in 1960 (Weatherston and Smith 1960). These systems proposed to rotate a solid material past an internal heat source and then to space where the heat could be rejected through radiation. In a majority of these systems, heat was transferred to the solid material through either conduction or convection. An extension of this concept that has been proposed for high-temperature ranges such as those found in reactor cores is referred to as the radiatively cooled, inertially driven nuclear generator (RING) heat-rejection system (Apley and Babb 1988). In this system, reactor waste heat is radiatively transferred from a cavity heat exchanger to the rotating ring. Although at low temperatures conduction and/or convection can reduce the size of the primary/secondary interface, at higher temperatures radiative heat transfer becomes attractive. The RING power system takes advantage of the need to offset the reactor from the mission platform (for radiation field reduction) by using the space between the reactor and the mission platform (and the boom structural assembly) to support four counterrotating, 90° offset, coolant-carrying rings. The proposed rings are segmented, finned, thin-walled pipes that are filled with liquid lithium.

The enclosed cavity heat exchanger allows a higher emissivity material to be used, and because the configuration is protected, the primary coolant tubes can be placed closer to the heat transfer surface. The cavity configuration also increases the hemispherical emissivity of the wall material (Siegel and Howell 1980).

Moving-Belt Radiators

Another advanced radiator concept is the moving-belt radiator (MBR) (Teagan and Fitzgerald 1984). This concept was being developed under contract to NASA Lewis Research Center contract during the latter eighties. The basic operation of an MBR is illustrated in figure 8, where a cylindrical belt is rotated about a fixed center through some type of driving mechanism attached to the spacecraft. Heat collected inside the spacecraft is transferred from a primary heat transport loop to the belt through solid-to-solid conduction or directly through convection. As the belt rotates into the spacecraft heat

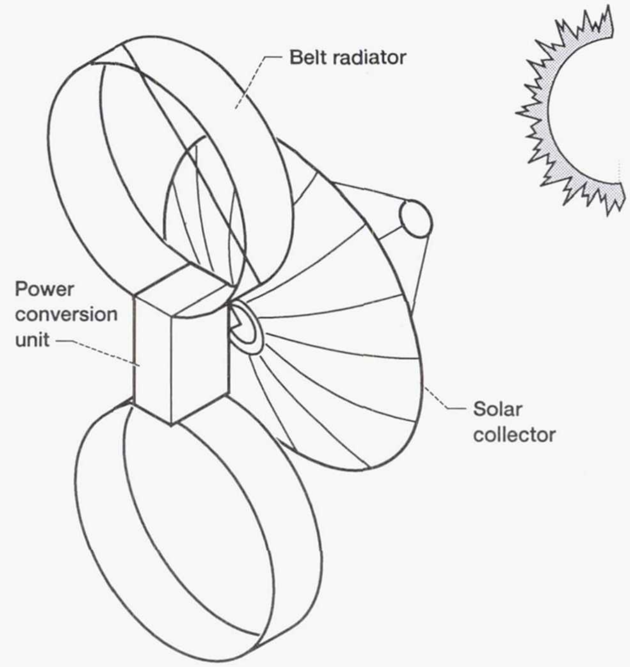

Figure 8.—Moving-belt radiator concept.

exchanger it absorbs heat, and while rotating through space it rejects heat by radiation. Several materials have been proposed for the belt material, including homogeneous solids, or two solid belts with a phase-change material between them. A follow-on report discusses analytical and experimental investigations of the rotational dynamics of this system along with methods for transferring heat to the moving belt, deployment and stowage, and fabrication. Also, life-limiting factors such as seal wear and micrometeoroid resistance are identified (White 1988).

The MBR was projected to be only 10 to 30 percent as massive as advanced heat pipe radiators, and it could operate without exposing the working fluid to space, thereby reducing vaporization losses. The major technological challenge appears to be maintaining the stability of a rotating belt during spacecraft attitude maneuvers. Although other issues, such as long-term reliability of the roller drive mechanism, must be solved, this concept compares favorably with the 5 to 8 kg/m^2 space-constructable heat pipe radiator at both 300 and 1000 K.

A concept similar to the MBR is the liquid-belt radiator (LBR), which was also proposed by Teagan and Fitzgerald (1984). In the LBR (fig. 9), a thin screen or porous mesh structure supports a low vapor pressure liquid by capillary forces. This screen is drawn through a liquid bath where warm liquid is picked up and retained in the screen material. The screen and liquid form a ribbon which is then rotated through space, where heat is rejected through radiation. The advantages and disadvantages with this type of radiator system are similar to those of the MBR. However, in this case the liquid must have a very low vapor pressure (less than 10^{-8} torr) over the entire operating temperature range to prevent evaporative losses.

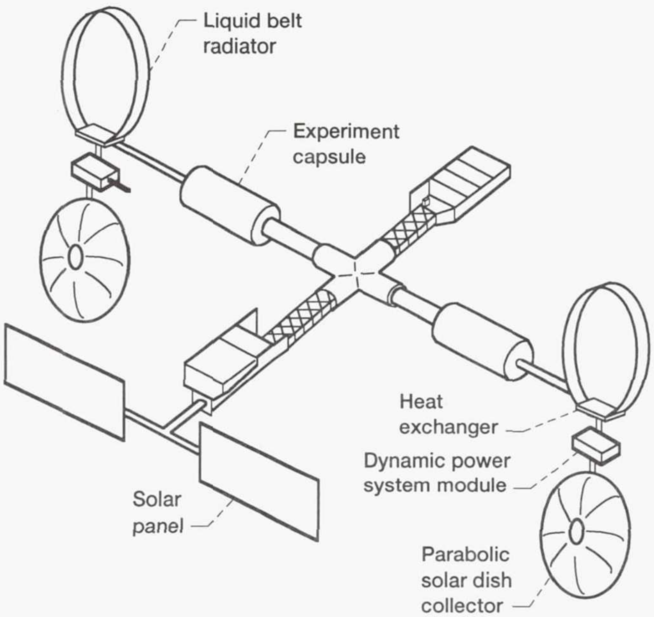

Figure 9.—Artist's schematic of liquid belt radiator.

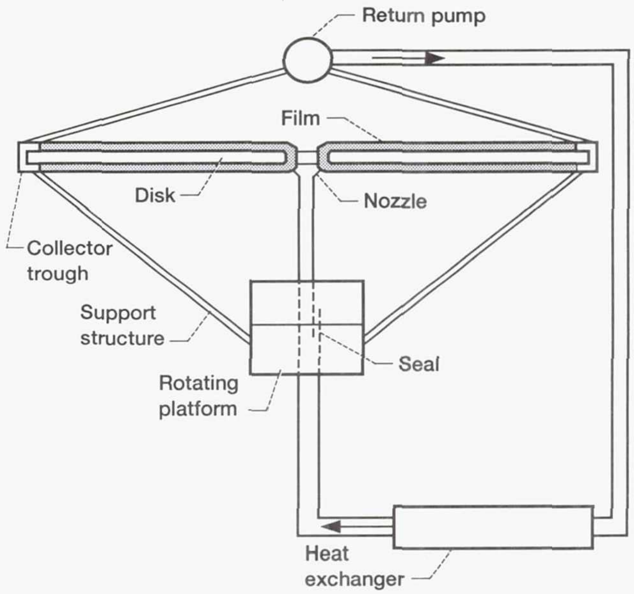

Figure 10.—Rotating film radiator schematic.

Several materials have been proposed, including diffusion pump oils, gallium, lithium, and tin. The material selection depends primarily on the temperature range of interest, with the oils limited to about 350 K and the liquid metals being applicable over a wide temperature range, as high as 2000 K. For space radiator applications, the maximum operating temperature is expected to be in the 1000 K range for thermionic power systems. Although the proposed mode of operation is in the sensible heat mode, in some situations, it may be desirable for the LBR to operate in the latent heat mode. When this is done, the liquid changes phase during its traverse through space. Clearly, the mode of operation would depend on material selection, operating temperatures, and heat-rejection requirements. Parametric analyses (Teagan and Fitzgerald 1984) indicated that the LBR could reduce the radiator mass by as much as 70 percent of space-constructable state-of-the-art heat pipe radiators. However, the Advanced Radiator Concepts (ARC) program, to be discussed in the second part of this report, has demonstrated reductions in heat pipe specific mass by a factor of 3 to 4 over the state-of-the-art heat pipe technology used by Teagan and Fitzgerald for their basis of comparison.

Rotating Film Radiator

Figure 10 depicts another advanced radiator concept that uses a thin liquid film: the rotating film radiator (Song and Louis 1988). As shown, this concept uses a rotating disk with a thin film of liquid flowing radially. Initially, the proposed working fluid, toluene, is injected at the center and the flow is split equally between the two surfaces of the disk. The fluid then spreads into thin films which facilitate radiation of heat to space. The disk's rotational speed controls the thickness, velocity, and flow regime of the film. Upon reaching the outer circumference of the disk, the fluid is collected and returned to the center, as illustrated. Preliminary analysis for this concept (Prenger and Sullivan 1982) indicates that the rotating film radiator can achieve a specific mass of 5.5 kg/kW or 3.5 kg/m^2, based on total emissivities in excess of 0.3. Hence, it cannot compete with advanced heat pipe radiators (to be discussed in part II), which achieve equal or lower specific mass at surface emissivities of 0.85 to 0.9 and thus require only a third of the surface area to reject the same amount of heat.

Liquid Droplet Radiator

The liquid droplet radiator (LDR) concept retains the low-mass advantages of a disk radiator. As illustrated in figure 11, a warm, low vapor pressure working fluid is projected from a droplet generator, where the liquid absorbs heat, to a droplet collector, which collects the radiatively cooled droplets in a rotating drum (Mattick and Hertzberg 1981). Because of the large surface area of the droplets, this type of system has the additional advantage of greatly reduced mass, especially with paired modules, which eliminates the need for a long return loop for the liquid. These paired modules would be connected by a structural tie rod, thus maintaining the proper alignment between droplet generators and collectors. The generator is a pressurized plenum with an array of holes or nozzles to form liquid jets that break up into droplets via surface tension instability. A piezoelectric vibrator, which rapidly varies the pressure of the fluid, can also be employed to control the drop size and spacing. Droplets could be generated and collected, and heat transferred to the liquid, with only modest extensions of conventional technology. LDR's have a large surface area

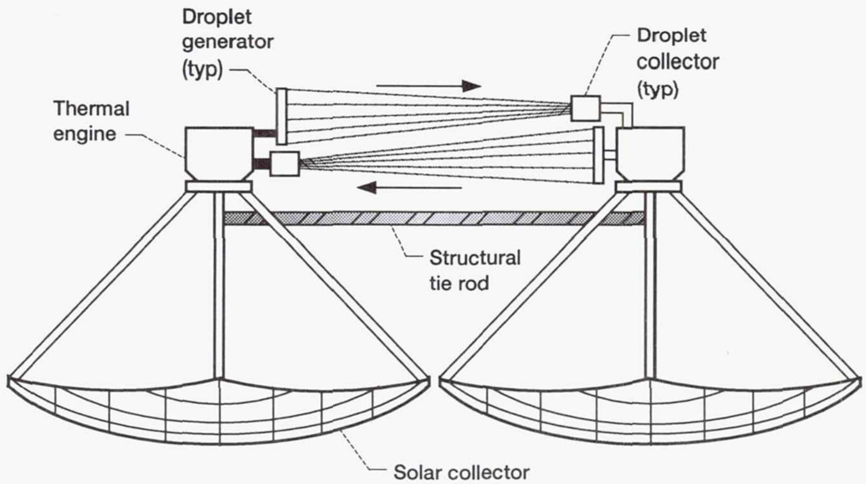

Figure 11.—Dual-module solar power satellite with liquid droplet radiator.

unit per unit mass, or low mass per unit radiating area, but this advantage is offset to some extent by the lower effective emissivity of the droplet sheet than that of advanced heat pipe radiators. However, proponents during the last decades argued that with low vapor pressure liquids, which are available over a wide radiating temperature range (250 to 1000 K) with negligible evaporation loss (silicone oils, 250 to 350 K; liquid metal eutectics, 370 to 650 K; and liquid tin, 550 to 1000 K), the LDR could be adapted for a wide range of heat-rejection applications (Elliott 1984).

A governing factor in the design of LDR's is the mass loss via evaporation. The mass required to replenish the evaporation must be included in the overall radiator mass for comparison with other systems. However, for rejection temperatures between 300 and 1000 K, liquids are available with low enough vapor pressures that evaporation losses can be considerably smaller than the radiator mass, even for operational lifetimes of 30 years. Thus droplet radiators were considered suitable for a wide range of applications—from heat rejection in high-temperature thermal engines, where rejection temperatures might be in the 500 to 1000 K range, to cooling of photovoltaic cells and heat rejection from refrigerators, where rejection temperatures would be in the 250 to 350 K range (Mattick and Hertzberg 1981).

An extension of the LDR, the liquid sheet radiator (LSR), has also been proposed. The operation of this type of system is similar to that of the LDR with the exception that a continuous liquid sheet, rather than a multitude of individual droplets, is used to reject heat. Because the narrow slits that produce sheet flow can be fabricated without the precision machining techniques required for a large number of small orifices, this system reduces the level of technology development required. In addition, the LSR requires less pumping power because of the reduced viscous losses, and it offers a simplified collection system because of a self-focusing feature (Chubb and White 1987). Both the LDR and the LSR are compatible with power systems that have near constant heat-rejection temperatures (Juhasz and Chubb 1991). However, they are not compatible with closed-cycle gas turbine power systems, which must reject heat over a broad temperature range (Juhasz and Chubb 1991; Juhasz, El-Genk, and Harper 1993). A recent status report on LSR development (Chubb, Calfo, and McMaster 1993) summarizes the work done on sheet stability and points out the need to conduct sheet emissivity measurements and to develop a sheet fluid collector before a viable LSR can be demonstrated.

Curie Point Radiator

The Curie Point Radiator (CPR) maintains the low mass advantage of the LDR and is similar in operation with one major exception. The CPR uses a large number of small, solid ferromagnetic particles (Carelli et al. 1986). These particles are heated to a temperature above the Curie point, the point at which a ferromagnetic material loses its magnetic properties, and are ejected from the heat source toward a magnetic field. As the particles radiate heat to space and cool, they regain their magnetic properties and are collected by a magnetic field collector. The CPR has all of the advantages of the LDR, such as low mass-to-radiating-area ratio, reduced mass for micrometeoroid protection, and a small mass of radiating particles that represents only a minor fraction of the total. In addition, the unique characteristics of the ferromagnetic particles result in several other significant advantages, including (1) a particle inventory that can be actively controlled, thereby reducing the loss of particles, (2) particles that can be coated to increase surface emissivity (a value as high as 0.9 can be achieved with SiC coating), and (3) elimination of the need for strict temperature control. The key disadvantage is the possibility of magnetic perturbations to other components of the spacecraft. Also, the problems of transferring spacecraft reject heat to the particle stream and the actual mass transport of the particles through the power system heat exchanger have not been solved.

Rotating Bubble-Membrane Radiator

Perhaps the most promising alternative to space-constructable heat pipe radiators, after LDR technologies, is the rotating bubble-membrane radiator (Webb and Antoniak 1988). A rotating bubble-membrane radiator functions as a two-phase, direct-contact heat exchanger. This hybrid radiator design incorporates the high surface heat fluxes and isothermal operating characteristics of conventional heat pipes along with the low system masses normally associated with LDR's. As depicted in figure 12, a two-phase working fluid enters the bubble through a central rotation shaft where it is sprayed radially from a central nozzle. This combination of liquid droplets and vapor moves from the central portion of the bubble toward the inner surface, transferring heat by both convection and radiation. As the droplets move outward, they increase in size because vapor condenses on the droplet surface and droplets collide with each other. Upon striking the inner surface of the radiator, the droplets form a thin surface film. This film then flows toward the equator because of the rotationally induced artificial gravity. Heat transfer between the fluid and bubble radiator then becomes a combination of conduction and convection. As the fluid reaches the equator of the sphere, it is collected in a gravity well and pumped back to repeat the process.

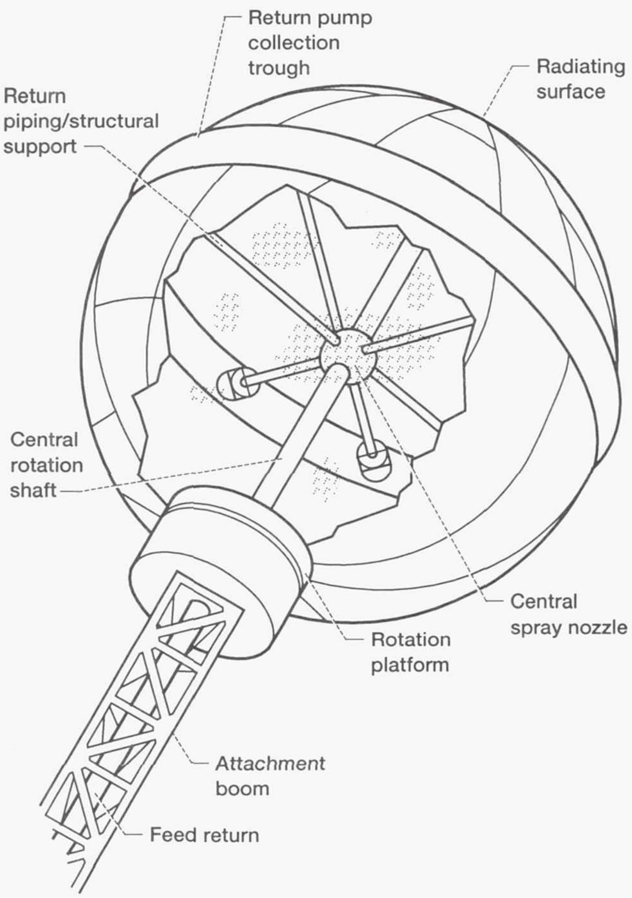

Figure 12.—Boom-mounted rotating bubble-membrane radiator.

To operate effectively in space, the rotating bubble-membrane radiator will include design features to minimize damage and to mitigate any coolant losses that may result from meteoroid and space debris impact. New high-strength, low-weight fiber and metallic alloy cloths show excellent promise for inhibiting micrometeoroid penetration of the rotating bubble-membrane radiator (Webb and Antoniak 1988). In addition, design options are being considered that would seal membrane penetrations and reduce coolant losses from micrometeoroid penetrations. Selection of materials for the thin-film membrane will be dictated by the desired operating temperature. Candidate materials include carbon-epoxy compounds, silica, alumino-borosilicate, or silicon carbide cloth with metallic liners (Sawko 1983), and niobium-tungsten composites. The final selection of the envelope material will depend on the radiator fluid and its intended operating temperature. Pump selection also will be determined by the working fluid. Electromagnetic pumps are possible candidates for liquid metal coolants, and mechanical or electric pumps are favored for other applications.

Technology Comparisons

Among the various heat pipe technologies considered for advanced heat-rejection systems (see table I), external artery and conventional, axially grooved heat pipes have the greatest heat-rejection capabilities. For high peak loads, expandable roll-out fin radiators with pulsed heat absorption capability offer a considerable weight savings over conventional tube and fin radiators. However, further study is necessary to reduce their vulnerability to micrometeoroids and to improve the header/fin heat exchanger design and the operating characteristics (Ponnappan, Beam, and Mahefkey 1984). Among the inflatable radiator concepts previously developed, a retractable bellows configuration with a stationary sponge appears to be the best candidate. Although previous analyses indicate that this type of system has good dynamic stability and excellent thermal behavior, additional investigations are required.

Several other advanced radiator systems have been proposed to reduce the mass requirement. Among these, the most actively pursued through the late eighties was the LDR, where a large number of submillimeter liquid droplets constitute the radiating surface. Although the LDR has the potential for substantial reduction in mass versus conventional radiator systems, problems associated with inventory losses due to vaporization, aiming inaccuracies, and splashing on the collector—which tend to increase the total system mass—must be addressed in future work. Another disadvantage of the LDR that must be resolved is that it is not suitable for missions requiring high maneuverability during full-power operation. Similar observations apply to the LSR, although it would be much easier and cheaper to fabricate the coolant fluid injectors for this concept. The MBR concept compares favorably with heat pipe radiators on the basis of specific mass. The biggest advantage is achieved

TABLE I. - COMPARISON OF ADVANCED RADIATOR CONCEPTS

Criterion[a]	SCR	ROF	RSR	MBR	LBR	RFR	LDR/LSR	CPR	RBMR
Weight	Mod.	Mod.	High	Mod.	Mod.	Mod.	Low	Low	Low
Reliability	Mod.	Avg	Mod.	Mod.	Mod.	Good	Mod.	Excel.	Good
Maintenance required	Low	Mod.	Low	Mod.	Mod.	Low	Mod.	Mod.	High
Technology readiness	Excel.	Mod.	Good	Poor	Poor	Mod.	Mod.	Poor	Poor
Life expectancy	Good	Good	Mod.	Mod.	Poor	Mod.	Excel.	Unkn.	Mod.
System complexity	Low	High	Mod.	High	Mod.	Mod.	High	High	High
Area required	High	High	Mod.	Mod.	Mod.	Mod.	Mod.	Mod.	Low
Performance	Excel.	Unkn.	Good	Unkn.	Unkn.	Mod.	Good	Unkn.	Mod.
Life cycle cost	Low	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Unkn.	Low
Micrometeoroid vulnerability	Mod.	High	Low	Mod.	Mod.	Mod.	Low	Low	High

[a]SCR space-constructable radiator
RSR rotating solid radiator
LBR liquid belt radiator
LDR liquid droplet radiator
LSR liquid sheet radiator
ROF roll-out fin radiator
MBR moving belt radiator
RFR rotating film radiator
CPR Curie point radiator
RBMR rotating bubble membrance radiator

with the hybrid belt system that exploits the phase-change potential of an LBR, yet offers high surface emissivities over a broad range of temperatures. However, control of the belt shape under microgravity operating conditions and long-term reliability of the roller drive system are serious problems. According to its proponents, the CPR, which utilizes the ferromagnetic properties of radiating particles, represents a unique concept that offers significant advantages in mass, high reliability, and a practically unlimited temperature range (Carelli et al. 1986). However, some key drawbacks, including heat transfer to and actual mass transport of the particles through the power system heat exchanger, and the possibility of magnetic perturbations to other spacecraft components, had not been resolved at the time of program termination.

Although the SCR is the most developed of the concepts and is a proven, reliable technology, additional investigations into the behavior during heat pipe startup from a frozen working fluid state and the effect of on-orbit accelerations are needed. Although rotating bubble-membrane radiators and rotating film radiators presently lack the technical maturity of heat pipe radiators, rotating machinery and shaft vapor seals to space have proven effective and do not require additional development. With MBR's, seals must wipe off the working fluid without allowing leakage or damage to the belt as the belt exits the heat exchanger. In contrast, the LDR, CPR, and rotating bubble-membrane radiator require presently nonexistent technologies that must be completely developed, tested, and qualified. LDR's require a droplet generator/collector combination with a high degree of aiming accuracy. CPR's require a collector with a magnetic field generator and an effective heat exchanger to transfer heat to the solid particles from the working fluid.

Part II.—Highlights of the NASA Lewis Civil Space Technology Initiative Thermal Management Program

Civil Space Technology Initiative (CSTI) thermal management related work at Lewis (to be concluded during 1994) has been an integral part of the NASA CSTI High Capacity Power Program and, specifically, of the Tri-Agency (Department of Defense, Department of Energy, and NASA) SP–100 nuclear reactor space power program (Winter 1991).

The goal of the Lewis thermal management effort (Juhasz 1991) is to develop near-term space radiator and heat-rejection system concepts, optimized for a spectrum of space power conversion systems for planetary surface (lunar base) and nuclear propulsion applications for deep-space, long-duration missions needed for the Space Exploration Initiative (Bennett and Cull 1991). The power, or energy, conversion system concepts range from static systems, such as thermoelectric or thermionic, to dynamic conversion systems based on heat engines, such as the Stirling engine or the closed-cycle gas turbine, also known as the Closed Brayton Cycle (CBC). Although the principal heat sources for these systems are nuclear (Juhasz and Jones 1987), the technology being

developed for the heat-rejection subsystem is also applicable to low-Earth-orbit (LEO) based dynamic power systems with solar energy input, using a concentrator and heat receiver. Brandhorst, Juhasz, and Jones (1986) studied such systems as alternatives to photovoltaic power systems. The performance goals for the advanced radiator concepts being developed are lower radiator mass (specific mass of 5 kg/m^2 or lower) at a surface emissivity of at least 0.85 over the entire operating temperature range, greater survivability in a micrometeoroid or space debris environment (up to 10 years), and a subsystem reliability of 0.99 or higher. These performance goals may be realized by radiator segmentation and parallel redundancy, using a large number of heat pipes. Achieving these goals may reduce the SP–100 radiator specific mass by a factor of 2 or more over the original baseline design and may lead to even greater mass reductions for radiators used in contemporary spacecraft.

The project elements (fig. 13) include development of advanced radiator concepts under Lewis-managed contracts and a NASA/Department of Energy interagency agreement, as well as in-house work directed at radiator design for optimum power system matching and integration. In-house and university-supported heat pipe research and development also is being carried out. This work includes analytical computer code development for predicting heat pipe performance, both under steady state and transient operating conditions, along with experimental testing to validate the analytical predictions.

Continued research on radiator surface treatment techniques (surface morphology alteration) is contributing to the in-house advanced development program. This research is aimed at enhancing surface emissivity and resistance to atomic oxygen attack.

The development of new radiator materials with high strength-to-weight ratios and high thermal conductivity (such as carbon-carbon composites for lightweight radiator fins) is another major objective. Figure 14 shows the project plan. Note that because of funding constraints, the development of the far-term innovative radiator concepts discussed in Part I, such as the LDR and the MBR, is not being actively pursued. Instead, technologies that could be developed before the end of the decade are being concentrated on for both surface power and nuclear electric propulsion (NEP) applications. Near-term applications to small spacecraft and technology transfer to possible terrestrial uses are also being considered.

The remainder of this report reviews the major project elements, concentrating on the contracted efforts that account for the major portion of the baseline budget.

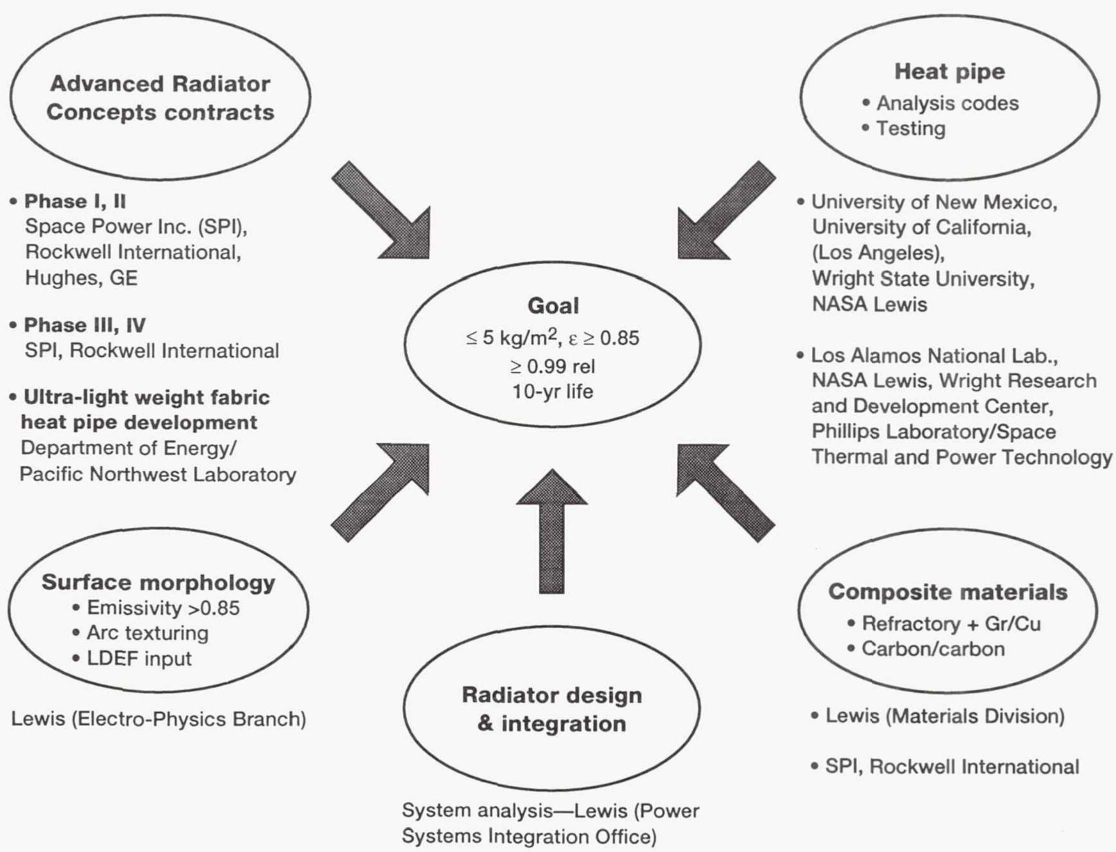

Figure 13.—Lewis thermal management project elements. (LDEF, the Long-Duration Exposure Facility, was launched in 1984 and retrieved from space in 1990.)

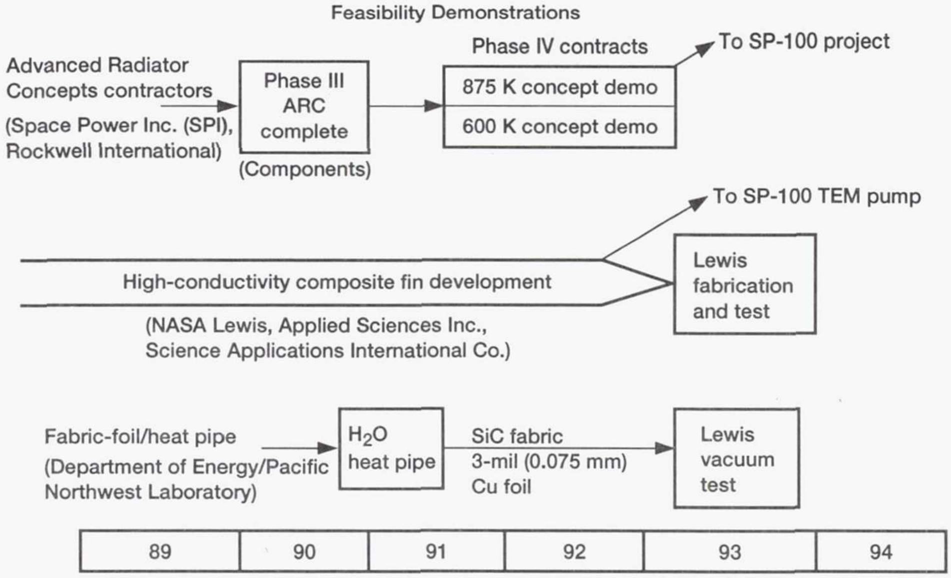

Figure 14.—Thermal management project plan.

Advanced Radiator Concepts Development Contracts

The Advanced Radiator Concepts (ARC) contractual development effort is aimed at the development of improved, lightweight space heat-rejection systems, with special emphasis on space radiator hardware, for several power system options, including the thermoelectric and Free Piston Stirling (FPS). The targeted improvements will lead to lower specific mass (mass per unit area) at high surface emissivity, higher reliability, and higher survivability in a natural space environment, thereby leading to longer life for the power system as a whole. As stated earlier, specific objectives are to reduce specific mass to <5 kg/m^2 with radiator surface emissivities of 0.85 or higher, at typical radiator operating temperatures and with reliability values of at least 0.99 for the heat-rejection subsystem over a 10-year life. Although the above specific mass figure does not include the pumps and the heat transport duct, it represents about a factor of 2 mass reduction over the baseline SP–100 radiator, and it implies an even greater mass savings for the state-of-the-art heat-rejection systems used in current spacecraft applications.

Phases I, II, and III of the ARC contracts have been completed by both contractors: Space Power Inc. (SPI) of San Jose, California, and Rockwell International of Canoga Park, California. On the basis of the phase III results, both contractors were selected to proceed into phase IV—component-level development, fabrication, and demonstration—to be accomplished over a 2-year period and to be concluded by early 1994.

SPI is developing both a high-temperature heat-rejection option (800 to 830 K) applicable to thermoelectric power conversion systems, and a low-temperature option (500 to 600 K) applicable to Stirling power conversion systems. Rockwell has focused on heat-rejection technology for the higher temperature thermoelectric power systems.

Contract NAS 3-25208 With SPI

Among the advanced concepts proposed by SPI are the Telescoping Radiator (Begg and Engdahl 1989 and Koester and Juhasz 1991) for multimegawatt thermoelectric or liquid metal Rankine power systems (fig. 15), and the Folding Panel Radiator (Koester and Juhasz 1991) (fig. 16) for the 500 to 600 K heat-rejection temperature range. The latter concept was based on a pumped binary lithium/sodium potassium (Li/NaK) loop, motivated by a desire to avoid the need for mercury heat pipes (HgHP) and their potential adverse effects on spacecraft electrical systems. Such HgHP radiators were originally planned for an FPS power system that rejects heat in the above temperature range.

Li/NaK Binary Pumped Loop

A detail of a typical Li/NaK heat-rejection loop, which also uses high-conductivity fins for heat transport is illustrated in figure 17. As indicated in figure 18(a), the advantage of using a Li/NaK mixture, rather than NaK alone (melting point, 261 K), lies in its combining the high heat capacity and low pumping power of Li (melting point, 452 K) with the liquid pumping capability of NaK, down to its freezing temperature of 261 K.

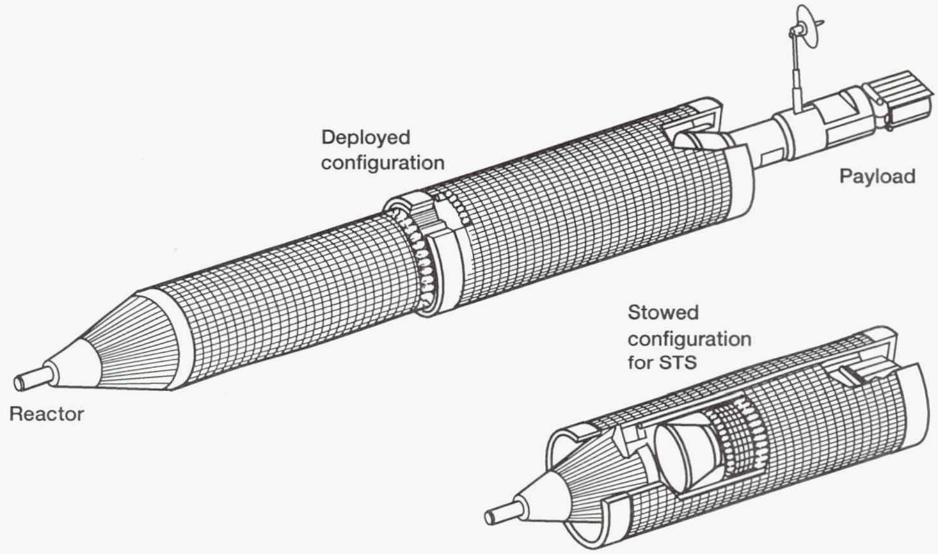

Figure 15.—Multimegawatt, telescoping cylinder heat pipe radiator concept; longitudinal potassium heat pipes with circumferential heat pipe fins.

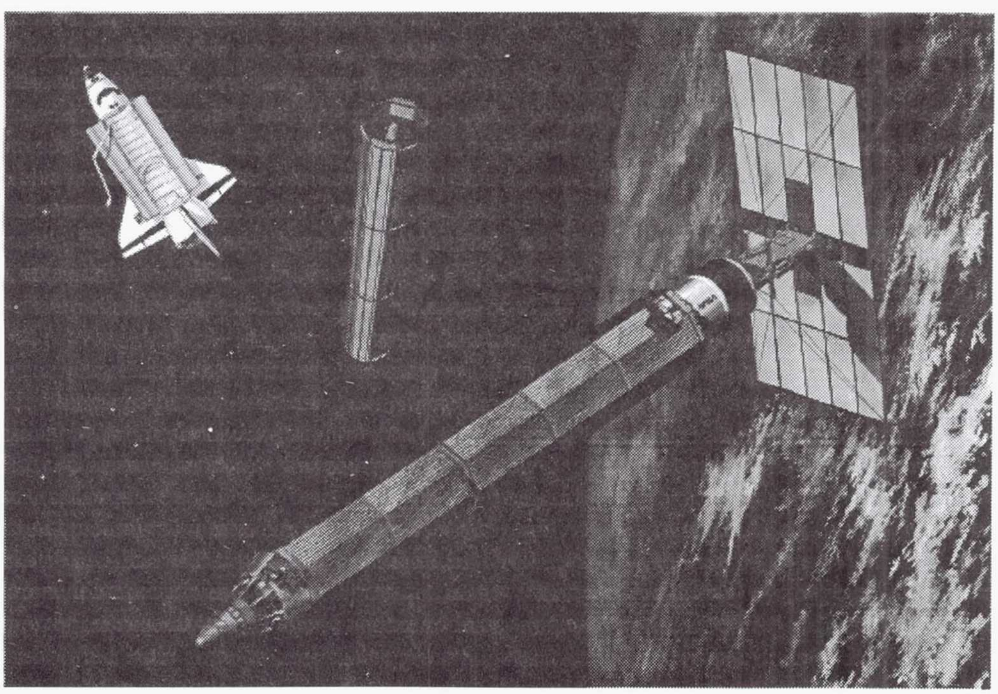

Figure 16.—Folding-panel heat pipe radiator concept.

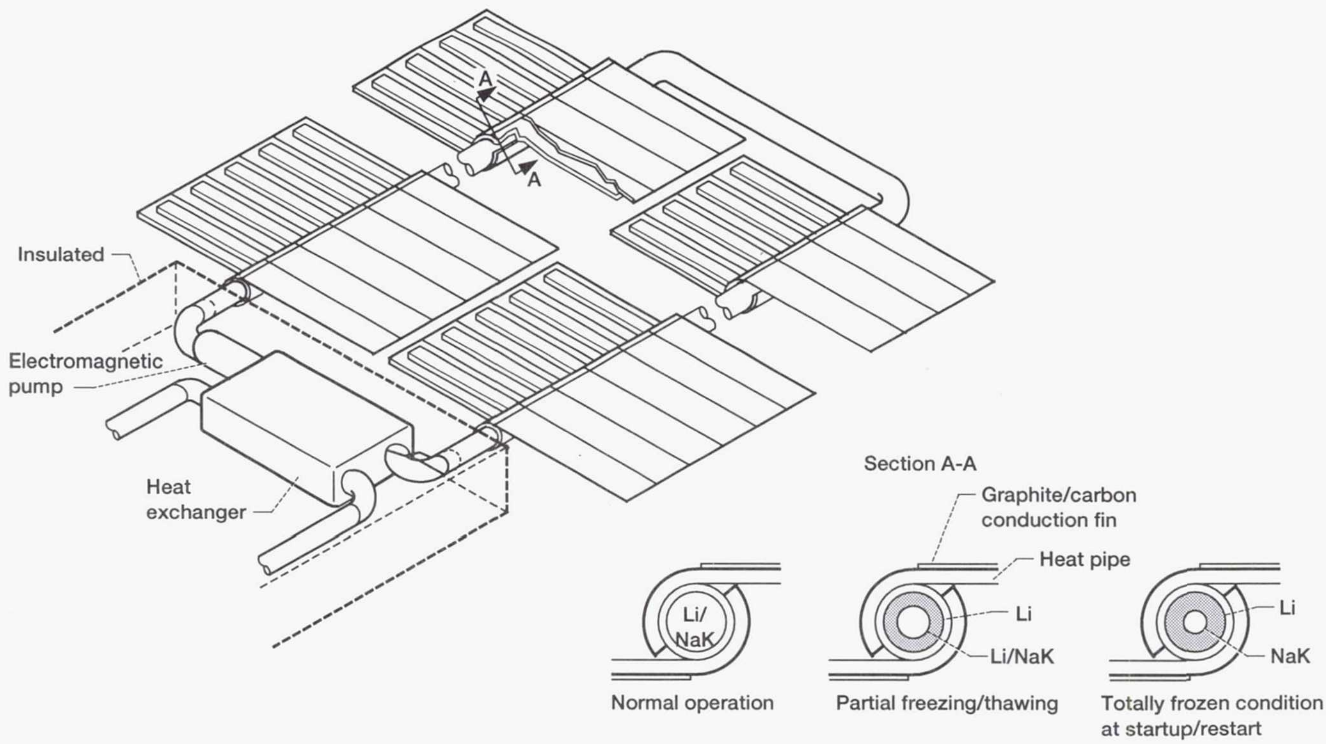

Figure 17.—Pumped Li/NaK binary loop radiator concept.

To illustrate the operation of this binary loop during system startup and shutdown, a brief explanation is in order. During startup (with Li frozen), liquid NaK would be pumped through the inner cores of radiator tube passages in hydraulic contact with the frozen layers of Li coating the inner passage surfaces. As the NaK is heated during power system startup, it eventually melts the solid Li annuli by direct-contact, forced-convection heat transfer. The melted Li progressively mixes with the NaK to form the all-liquid Li/NaK coolant. Conversely, on shutdown of the power system, the molten Li with its higher freezing point will selectively "cold trap," or freeze, on the inner passage surfaces as their temperatures drop below the 452 K freezing point, while the NaK continues to be pumped in its liquid state through the inner cores of the radiator passages.

Tests conducted thus far, using a trunnion-mounted test loop, which can be rotated about pitch and roll axes to isolate gravity effects (fig. 18(b)), have demonstrated the feasibility of the concept up to Li volume fractions of 50 percent. In particular, the feasibility of a heat-rejection system based on a binary Li/NaK pumped loop was demonstrated during transient operating conditions, representative of both the cooldown (Li freezing) and warmup (Li melting) phases of typical alkali metal heat-rejection pumped loops. At certain operating conditions, the thawing process had to be controlled very closely to avoid plugging the test section flow passage downstream of the melt front at certain operating conditions. Current efforts focus on widening the operating envelope by a variety of techniques. One of these involves the use of fine mesh screens which act as semipermeable membranes to NaK under certain operating conditions.

A two-dimensional computer analysis of the cooldown (freeze) and warmup (thaw) processes also has been completed, including color graphics output. Although the flat flow channel cross-sectional geometry assumed in the analysis deviated from the cylindrical flow channel used in the experimental loop, this computer code nevertheless permitted visualization of the basic phenomena within the binary loop during the warmup and cooldown periods. A video tape of the analysis illustrates several cases with and without plugging of the flow channel due to Li freezing over the entire channel cross section. Time and funding permitting, freeze-thaw behavior at higher than 50 vol % Li will also be briefly explored (Koester and Juhasz 1994).

High-Conductivity Fin Development

Progress also was made by SPI in its work with innovative subcontractors, namely Applied Sciences Inc. (ASI) and Science Applications International Co. (SAIC), who have demonstrated considerable success in the development and fabrication of high thermal conductivity composite materials for space radiator fin applications. In particular, ASI has produced a composite by chemical vapor deposition and densification of closely packed (up to 60 vol %) vapor-grown carbon fibers which was shown to have high thermal conductivity (near 560 W/m•K) at room temperature, and a density of 1.65 g/cm^3.

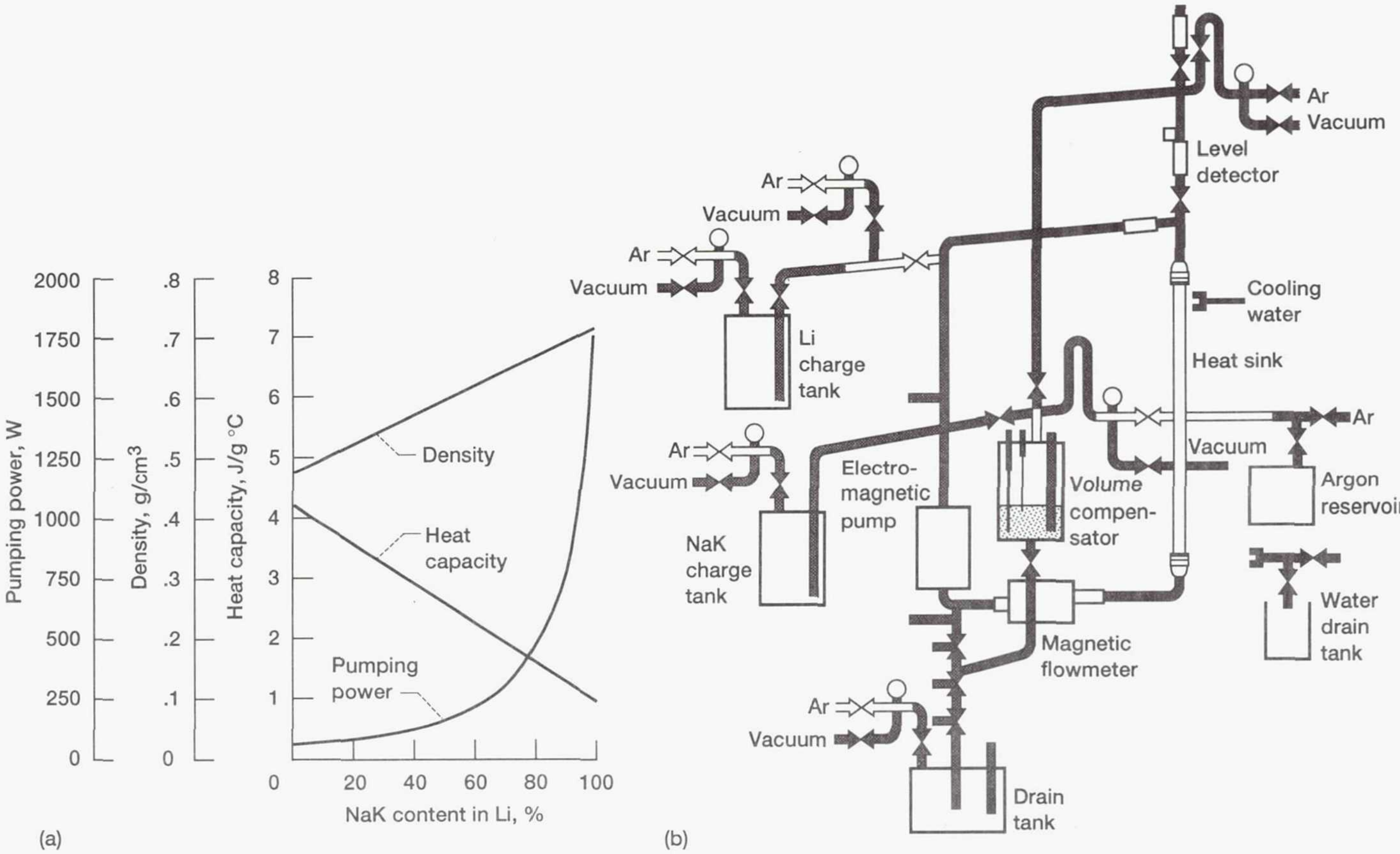

Figure 18.—Binary Li/NaK radiator development. (a) Pumping characteristics of Li/NaK mixtures. 5-MW transported; fluid ΔT = 100 °C; 15 parallel loops with 5-cm diameters. (b) Test loop.

Similarly, SAIC has successfully fabricated composites using short (about 0.01 m long) vapor-grown carbon fibers with a density of 1.6 g/cm^3 and a demonstrated conductivity of 470 W/m•K at operating temperatures near 600 K. A comparison of these properties with those of copper (density, 8.9 g/cm^3, and thermal conductivity, 380 W/m•K) reveals a significantly higher conductivity-to-density ratio for these composites.

Use of composite materials with specific thermal conductivity values at these levels for heat pipe fin applications permits increasing the fin length at constant fin efficiency, and it therefore has the potential of reducing radiator specific mass by over 60 percent for radiators that are radiative heat transfer surface limited. Recently, technology for joining the high-conductivity fins to the heat pipes by advanced brazing or welding techniques and processes that will lead to even higher composite thermal conductivity values also have been demonstrated (Denham et al. 1994).

Contract NAS 3-25209 With Rockwell International

A sketch of the Petal-Cone radiator concept being developed at Rockwell International (RI)(Rovang 1988) is shown in figure 19. Because each of the "petals," or radiator panels, is composed of a large number (384) of variable length carbon-carbon (C–C) heat pipes mounted transverse to the panel axis, a major objective of this effort is to develop these integrally woven graphite/carbon tubes with an internal metallic barrier that is compatible with the intended potassium working fluid.

C–C heat pipe tube sections with integrally woven fins were fabricated under phase III (Rovang et al. 1990). Highlights of the fabrication process are illustrated in figure 20. Because of its low cost, commercial availability, and ease of weaving, a T–300 fiber was selected for this demonstration of C–C heat pipe preform fabrication. This polyacrylonitrile (PAN) fiber was judged to represent a tradeoff between high elastic modulus, and consequently ease of handling and weaving, and medium thermal conductivity (80 W/m•K), in contrast to some very high conductivity fibers which, however, may be brittle and difficult to weave.

Several fiber architectures were investigated before settling on an angle interlock, integrally woven concept. In this design, the axial fiber bundles, referred to as warp weavers, are woven in an angle interlock pattern, repeatedly traversing from the inner diameter to the outer diameter surface of the tube. An

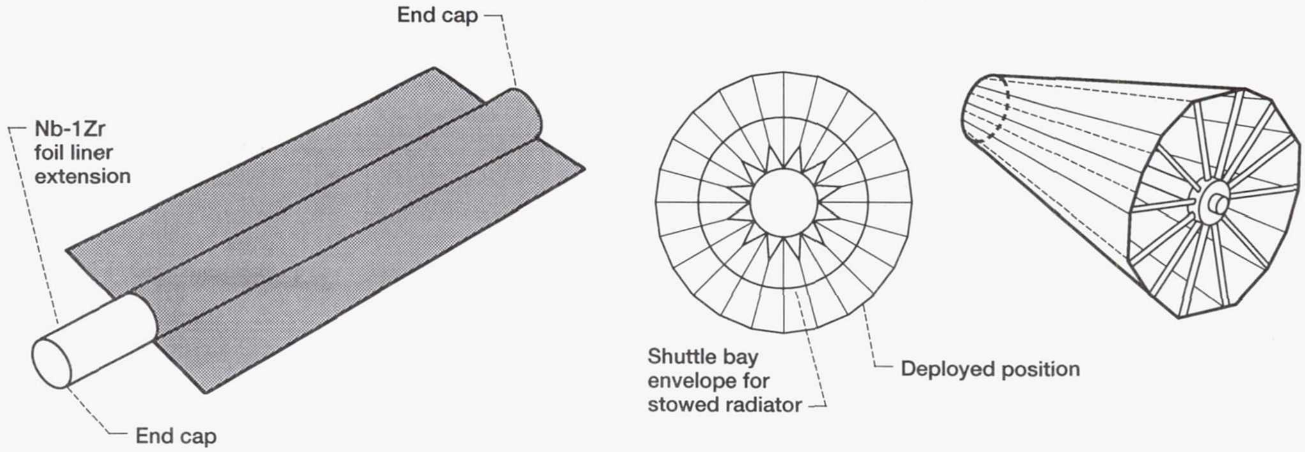

Figure 19.—Petal-cone heat pipe radiator concept. (a) Heat pipe. (b) Cone radiator (12 panels).

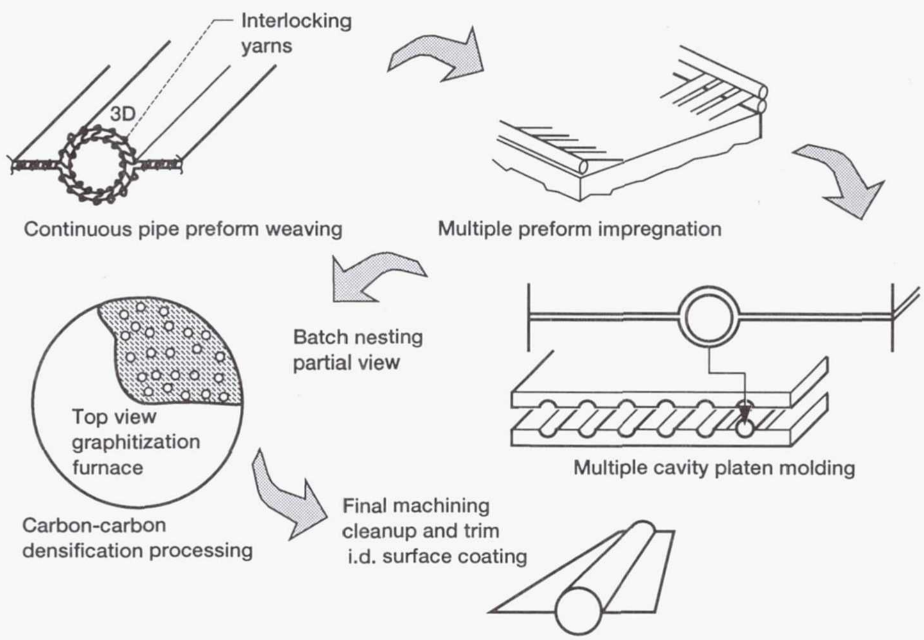

Figure 20.—Integral, pinned graphite-carbon heat pipe fabrication process.

unfilled "Novolack"/resole prepreg resin was selected for prepregging the woven preforms followed by a low-pressure, high-temperature impregnation and carbonization process for densification of the composite.

Considerable progress was made in the development of internal metallic coatings to ensure compatibility of the heat pipe surface with the potassium working fluid. A coating consisting of a 2 to 3 μm rhenium sublayer with a 70 to 80 μm niobium overlayer emerged as the final recommended coating design. Because of funding and time limitations, however, this final coating design and the recommended method to achieve it, a novel chemical vapor deposition process that uses a moving heat source, could not be fully implemented during phase III. Other coating approaches which were tried achieved incremental improvements over each previous coating attempt, but a constant thickness coating over the full-length of the tube without any flaws or imperfections could not be achieved.

Because of these coating problems, RI was directed at the beginning of phase IV to use a thin-walled metallic liner to safely contain the heat pipe working fluid instead of using the metallic coating that had been under development during phase III. Another advantage of the metal liner approach was that the heat pipe evaporator could be formed by simple extension of the liner beyond the C–C shell.

Concurrently with this task, a high-temperature braze or other joining process was developed to ensure good mechanical and thermal contact between the thin metallic liner and the C–C internal tube surface. Bonding of the entire liner surface to

a finned 0.3 m long C–C tube also has been achieved by use of ternary braze alloys, such as Silver ABA or Cusil ABA. This was necessary to prevent partial separation and local collapse of the liner at conditions prior to launch, where the external atmospheric pressure exceeds the internal pressure of the working fluid.

Concerning the integral fin weaving process, using T–300 fibers, significant improvements were made, which lead to the elimination of a troublesome internal cusp formed at the fin-tube interface. This was accomplished by changing the weave architecture so that the outer, rather than the inner, plies were used to form the fins.

In addition to the fabrication and testing of a complete 2.5 cm o.d. heat pipe with a niobium/zirconium alloy liner and a T–300 composite shell, the fabrication of a higher conductivity composite (P95WG) finned heat pipe shell was also completed. With a measured conductivity of over 300 W/m•K for this composite, fin length could be doubled from 2.5 to 5 cm, thus reducing the specific mass (for one-sided heat rejection) to 2.9 kg/m^2, in comparison to 4.2 kg/m^2 for the T–300 composite. For two-sided heat rejection, as occurs with flat plate radiators, the above specific mass values are effectively cut in half (Juhasz and Bloomfield 1994). A recent update summarizing the fabrication and testing of the Rockwell/NASA C–C heat pipe is given by Rovang, Hunt, and Juhasz (1994).

Lightweight Advanced Ceramic Fiber Heat Pipe Radiators

The objective of this joint NASA Lewis, Air Force (Phillips Laboratory, Kirtland Air Force Base), and Department of Energy (Pacific Northwest Laboratories) program was to demonstrate the feasibility of lightweight, flexible ceramic fabric (such as aluminum borosilicate) metal-foil-lined heat pipes for a wide range of operating temperatures and working fluids. Specifically, the Lewis objectives were to develop this concept for application to Stirling space radiators with operating temperatures below 500 K, using water as the working fluid. The specific mass goals for these heat pipes were <3 kg/m^2 at a surface emissivity of at least 0.80.

Several heat pipes were built with titanium or copper foil material for containment of the water working fluid. A heat pipe with an 8 mil (0.2 mm) titanium liner, designed to operate at temperatures up to 475 K, was demonstrated at the 8th Symposium on Space Nuclear Power Systems (Antoniak et al. 1991).

An innovative Uniskan Roller Extrusion process was developed at Pacific Northwest Laboratories and used to draw 30 mil (0.75 mm) wall tubing to a 2 mil (0.05 mm) foil liner in one pass. Moreover, this process eliminated the need for joining the thin foil section to a heavier tube section for the heat pipe evaporator, which needs to be in tight mechanical and thermal contact with the heat-rejection system transport duct. End caps are attached to the evaporator and condenser ends of the tubular liner by specialized brazing or welding techniques. The liner fabrication technique also was applied to the Rockwell heat pipe fabrication discussed above, and it is expected to have broad application beyond the scope of this program. The water heat pipes fabricated for NASA Lewis by Pacific Northwest Laboratories were evaluated for performance and reliability at demanding operating conditions, including operating pressures up to 25 bar. Tests were conducted with and without wicks, with the heat pipes in various gravity tilt orientations from vertical to horizontal. In addition, several wick designs were tested for capillary pumping capability, both in ground tests and in low-gravity, KC-135 aircraft testing (Antoniak et al. 1991).

Future work in this area needs to focus on perfecting the heat pipe fabrication procedure by using very thin (1 to 2 mil (0.025 to 0.05 mm)) foil liners, internally texturized by exposure to high pressures. With sufficient development, the textured internal surface may provide the required capillary pumping between the condenser and evaporator. Because of the high operating pressures required with water (over 16 atm), hyper-velocity and ballistic velocity simulated micrometeoroid impact tests on thin-walled pressurized tubes enclosed in woven fabric will be needed to ascertain if secondary fragments from a penetrated heat pipe could cause neighboring heat pipes to fail. Another major challenge will be to design and fabricate a heat pipe with high-conductivity, lightweight fins as a first step toward lightweight radiator panels.

Supporting Project Elements

Space limitations prevent a detailed discussion of the remaining project elements referred to in figure 13. However, a brief paragraph highlighting these activities is warranted. As mentioned previously, the system integration studies performed at Lewis guide the overall thermal management work by providing the proper application for it. As shown by Juhasz and Chubb (1991), for example, an LSR with lighter specific mass than a heat pipe radiator will not necessarily benefit all power conversion systems equally. As discussed in the reference, the LSR (or the LDR) concept is not suited to the relatively steep heat-rejection temperature profile of a Closed-Brayton-Cycle power system. However, it does work well with a Stirling power system, which rejects heat at a near constant temperature. For a further example of how radiator-power system integration studies are used to ascertain radiator-induced power system performance degradation, refer to figure 21. The curves illustrate the reduction in power output and efficiency for both Brayton and Stirling power systems, resulting from a reduction in cycle temperature ratio due to a loss of radiator area. Such area loss may be caused, for example, by micrometeoroid damage. It should be noted that even with a loss of 50 percent of radiator area, a Stirling engine can still produce over 75 percent of its design power, whereas a Closed-Brayton-Cycle system produces over 65 percent of its rated output.

A typical example of radiator surface morphology alteration by arc texturing for emissivity enhancement purposes is

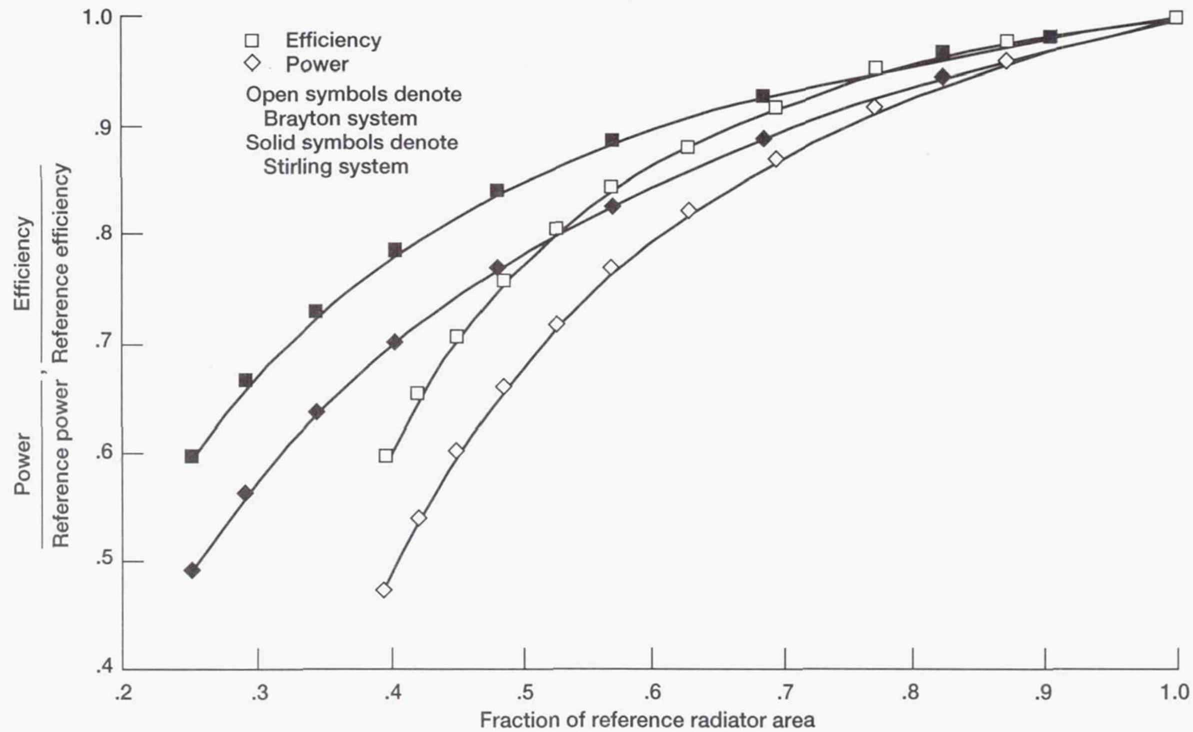

Figure 21.—Sample results from radiator-power system integration study.

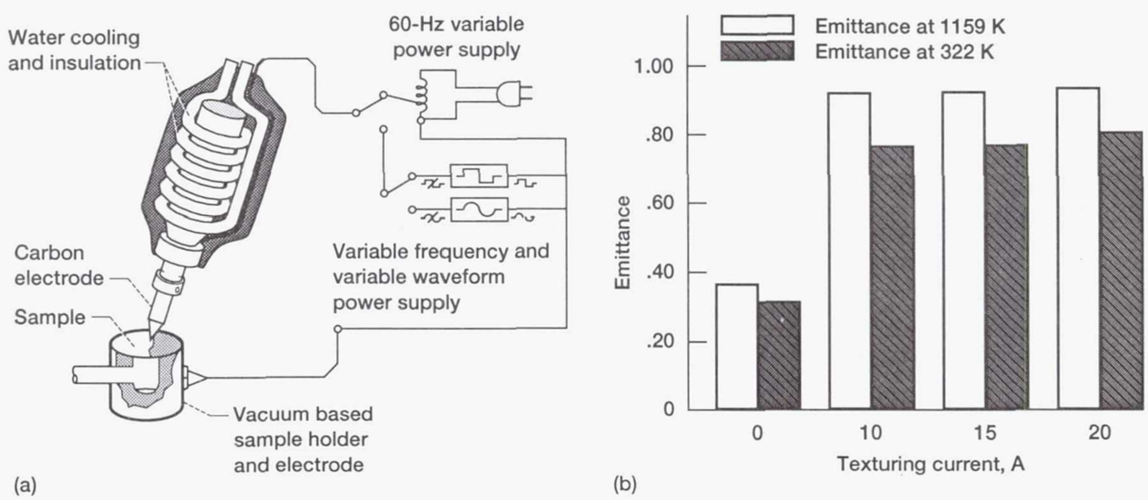

Figure 22.—Surface emittance enhancement by arc texturing. (a) Texturing equipment setup. (b) Emittance of graphite/copper samples.

shown in figure 22. Along with the arc-texturing apparatus in figure 22(a), the adjoining bar chart (fig. 22(b)) shows the surface emittance achieved with various arc current values for graphite-copper samples produced under the in-house materials program. Additional details of the emittance enhancement process and measurement techniques are discussed by Rutledge, Forkapa, and Cooper (1991). Rutledge, Hotes, and Paulsen (1989) detail the emittance enhancement of C–C composite surfaces by atomic oxygen beam texturing. A brief overview of the same topic is included in a CSTI status report (Winter 1991).

Heat pipe performance modeling, both under steady state and transient operating conditions, is being concluded at Lewis and under university grants with the University of California, Los Angeles; the University of New Mexico; and Wright State University. The objective of this work is to develop a capability to analytically predict transient operation of heat pipes, particularly during startup and cooldown. An especially important feature of this work is the development of an analysis code that can model startup for a variety of working fluids (including water and liquid metals) when the working fluid is initially frozen. Working versions of the codes have been developed, and validation of predicted performance by laboratory testing of heat pipes is under way at Lewis, Los Alamos National Laboratory, and Wright State University. Efforts also have been initiated to compile an experimental database by a systematic literature search and by close communication with other researchers in the field.

Concluding Remarks

The NASA Lewis Research Center's Civil Space Technology Initiative (CSTI) Thermal Management Program was designed to combine a number of project-oriented elements in order to accomplish the overall objective of reducing radiator specific mass by at least a factor of 2 at a subsystem reliability of 0.99 over a 10-year service life. Although the main focus was on support of the SP–100 program by advances in heat-rejection technology, the concepts and hardware developed under this program are expected to benefit space power systems in general, ranging from solar photovoltaic or solar dynamic systems, with a power level of a few kilowatts to future multimegawatt power systems with nuclear heat sources for planetary surface and nuclear (electric) propulsion applications. In spite of the termination of the SP–100 program, its major subsystem technology advances, especially in the thermal management area, are judged to be ready for on-orbit demonstration before the end of the decade. Thus, NASA's and the nation's long-term goals in space exploration and utilization may be realized sometime during the next century. In the mean time, terrestrial and small spacecraft applications of these technologies also will be pursued.

Acknowledgments

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13. ABSTRACT ***(Maximum 200 words)***

A two-part overview of progress in space radiator technologies is presented. The first part reviews and compares the innovative heat-rejection system concepts proposed during the past decade, some of which have been developed to the breadboard demonstration stage. Included are space-constructable radiators with heat pipes, variable-surface-area radiators, rotating solid radiators, moving-belt radiators, rotating film radiators, liquid droplet radiators, Curie point radiators, and rotating bubble-membrane radiators. The second part summarizes a multielement project including focused hardware development under the Civil Space Technology Initiative (CSTI) High Capacity Power program carried out by the NASA Lewis Research Center and its contractors to develop lightweight space radiators in support of Space Exploration Initiative (SEI) power systems technology.

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